MODELING AND SIMULATION OF SHUTTLE LAUNCH AND RANGE OPERATIONS

Jorge Bardina
NASA Ames Research center
Mail Stop 269-2, Moffett Field
California, USA 94035
Jorge.E.Bardina@nasa.gov

Rajkumar Thirumalainambi
SAIC @ NASA Ames Research center
Mail Stop 269-2, Moffett Field
California, USA 94035
rajkumar@mail.arc.nasa.gov

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ABSTRACT

The simulation and modeling test bed is based on a mockup of a space flight operations control suitable to experiment physical, procedural, software, hardware and psychological aspects of space flight operations. The test bed consists of a weather expert system to advice on the effect of weather to the launch operations. It also simulates toxic gas dispersion model, impact of human health risk, debris dispersion model in 3D visualization. Since all modeling and simulation is based on the internet, it could reduce the cost of operations of launch and range safety by conducting extensive research before a particular launch. Each model has an independent decision making module to derive the best decision for launch.

INTRODUCTION

The launch and range operations test bed is a full-scale virtual dynamic operations control center for simulation of launch, range and safety systems. It will have the capability of simulating a variety of missions, vehicles, flight anomalies, and globally dispersed range operation via the internet, allowing new information and human factors technologies to be tested. Developing models for analyzing ground operations, trajectory analysis, and flight operations in an integrated fashion will give in-depth understanding of the process for mission planners, safety analysts and ground controllers. Intelligent launch and range operations virtual test bed (ILRO-VTB) (Bardina and Rajkumar 2003) is the tool and the process to integrate information technology for analyzing end-to-end shuttle and space launch simulations with special features of virtual reality, scientific visualization, and command and control (Bardina and Rajkumar 2003). Initially four areas are focused in test bed viz., (i) Weather modeling (Rajkumar and Bardina 2003) (ii) Orbital dynamics and telemetry (Jensen et. al 1962) (iii) Range safety (gas and debris dispersion model) (iv) Decision modeling. For the Space Shuttle vehicles, weather forecasts are provided by the U.S. Air Force Range Weather operations facility at Cape Canaveral beginning at Launch minus 3 days in coordination with the National Weather Service Space Flight Meteorology Group (SMG) at Johnson Space Center in Houston. These include weather trends and their possible effects on launch day. A formal prelaunch weather briefing is held on launch minus one day which is a specific weather briefing for all areas of launch operations. The basic weather launch commit criteria focus on ambient temperature, wind speed, precipitation, lightning, type of clouds and cloud characteristics. In this paper, a decision support system for weather is constructed based on the real time data, which has been collected from different agencies (Rajkumar and Bardina 2003). During the launch, burning of the rocket engines during the first few seconds prior to and immediately following vehicle launches results in the formation of a large cloud of hot, buoyant exhaust products near the ground level which subsequently rises and entrains ambient air until the temperature and density of the cloud reach an approximate equilibrium with ambient conditions. The rocket engines also leave an exhaust trial from normal launches which extend throughout the troposphere and beyond. The toxic gas dispersion model calculates peak concentration and deposition downwind from normal launches. The required meteorological inputs for the dispersion model are vertical profiles of wind direction (Rawinsonde), wind speed, air temperature, pressure and dew point or relative humidity between the earth's surface and 3000 m. The toxic dispersion model is based on a Gaussian approach which is a practical

diffusion modeling tool (Boyd 1985 and Beychok 1995).

During a launch of a rocket under prevailing weather conditions, commanders at Cape Canaveral Air Force Station evaluate the possibility of wind blown toxic emissions reaching civilian and military personnel near the area (FAA 1999). The Air Force uses a model called "Launch Area Toxic Risk Assessment (LATRA)" which is based on Monte Carlo simulation with a limited amount of data for toxic response functions to humans (Hudson et. al. 1999; Bennett and McDonald 1999). The main focus of toxic chemical species is hydrochloric acid (HCL), nitric acid (HNO$_3$), and nitrogen dioxide (NO$_2$) which are non-carcinogenic chemicals as per United States Environmental Protection Agency (USEPA). Without specific incidence data (e.g. mortality, acute illness etc) on humans or animals, it is difficult to endorse a particular response model to predict incidences. In this paper, we have developed a hazard quotient model, which is a ratio of estimated exposure concentration (EEC) to a no observed effect limit (NOEL) or other reference toxicity value (RTV).

If there is a malfunction during launches, the launch will be aborted or destroyed. Before such a condition arises; Range Safety Officers simulate debris impact zone and its effects for nearby residents around launch pad. The destruct limit lines, chevron lines, downward range safety simulations, and nominal trajectory simulations are computed using various physical models (FAA 1999). In the following sections, the intelligent launch and range virtual test bed architecture is provided in detail and underlying models are also explained.

LAUNCH AND RANGE OPERATIONS TEST BED ARCHITECTURE

The intelligent launch and range simulation test bed uses the latest information technology to bring a real time simulation to the web. The test bed consists of four dedicated servers which cater the complex simulation, modeling, data acquisition, processing and storage. Tomcat servers serve as web servers and Java Servlets, Applets act as the frontend graphical user interface (Bigus and Bigus 2001; Watson 1997). There are legacy codes (written in FORTRAN) which are running as backend processes supplying input data to other models. Java

applications acquire remote data for weather models. The decision model is based on a backward chaining expert system where rules are derived from flight launch rules. The overall architecture of the intelligent launch and range test bed is shown in figure 1. The '*ILR01*' server is an independent web server, which processes various weather factors and automatically updates launch status for 'GO/NO-GO' scenarios (Rajkumar and Bardina 2003). In the back end, data acquisition, and processing of data is performed periodically by running a *cron* daemon. The '*ILR02*' server provides an analysis of different types of orbits for different types of rockets. The orbital dynamics is provided in three dimensions, so that telemetry data can be captured which will provide enhanced knowledge of flight status (NASA 1988).
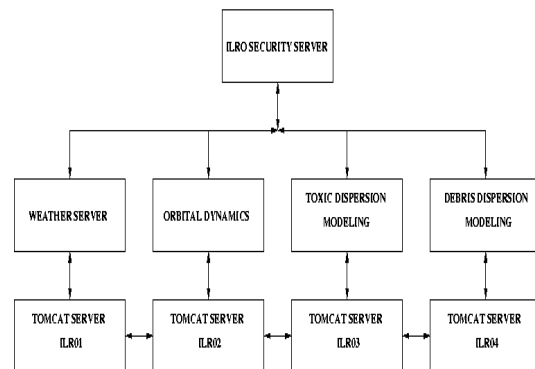

Figure 1 Intelligent launch and range test bed architecture

The toxic dispersion modeling coupled with geographical information system is served by '*ILR03*' server. The dispersion models used are based on Gaussian dispersion model concepts (Boyd 1985). The dosage and concentration formulas are defined in rectangular coordinates (NRC 1998 and 2000). The x-axis is directed along the axis of the mean wind direction and y-axis is directed perpendicular to the mean wind direction. Normally the origin of the coordinate system is placed at the launch pad. The '*openmap*' is a Java Beans based toolkit for building applications and applets needing geographic information. The *openmap* allows integrating many layers to represent various information like population density, gas dispersion, risk contour etc.

The '*ILR04*' supports the debris dispersion model, when there is a need for aborting a mission due to malfunction during launch. In the

present model, we have considered gravitational effect, air resistance, and particle/ground friction during settling of the particles. All particles are projected to disperse in an elliptical form where the particles hit the ground. If the particle has not reached the ground, there is a rotational effect for each particle in the air. In the following section each model is explained in detail and how these complex models interact with each other during simulation.

COMPONENTS OF THE MODELS

There are four major components involved in the simulation of launch and range safety systems to derive a 'GO/NO-GO' situation and they are : (i) Weather expert system (WES) (Rajkumar and Bardina 2003) (ii) Toxic gas dispersion model (Boyd 1985) (iii) Human health risk assessment model (Yassi 1998) (iv) Debris dispersion model and orbital dynamics (Lengyel 2004).

Weather Expert System

The weather expert system is launched by dedicated server as mentioned earlier and in the following sections the user interface, inference engine and knowledge base are discussed (Watson 1997).

User Interface

Java Servlet technology is adopted for accepting the user inputs and further analysis. In figure 2,

Figure 2 Graphical user interface of weather web server

there are 16 different buttons. The first four button rows deal with the US and North American continental weather system. The fifth button row provides information on global weather system including tropical cyclones. The

"Launch Decision" button activates the expert system and provides the expert decision for the shuttle launch. Except for the launch decision button, all other buttons invoke corresponding servlets. The servlets get the data or images from various sources across the US. The US weather button provides a 7 day weather forecast for a given zip code in the continental US. It provides a national weather service radar image and satellite image with daily weather forecasting. Apart from these images, specific weather details like humidity, wind speed, barometric pressure, heat index, and dew point are updated in hourly intervals. The U.S. Cloud classification obtained from the U.S. Naval postgraduate school at Monterey, California, lightning data from the National Lightning Detection Network, surface temperature, and wind speed from the National Weather Service are updated at 30 minute interval. Rawinsonde data are updated every day from the 45th Air Force wing located at Cape Canaveral, Florida. The sea state analysis is provided to the user to understand the booster rocket recovery. Weather criteria for an emergency landing at the TransOceanic Abort Landing Sites (TALS) is monitored by NOAA in Spain and North Africa. The downloaded data are processed for Florida state and Cape Canaveral and form an input to the expert system. When the user presses the "Launch Decision" an expert system inference engine checks the values against the weather rules and it provides the Shuttle launch decision by GO or NO-GO.

In figure 3, the expert decisions for the Shuttle launch are shown below the button groups. The green value contributes to the GO situation whereas red value contributes to the NO-GO situation.


Figure 3 Weather expert system output

If GO should occur, every value in the lower frame should be green. The present expert system provides the decision for a generic Shuttle launch. For specific Shuttle launches, more stringent rules have to be added to the knowledge base.

Inference Engine

The inference engine looks at the goal variable of the expert system. The inference engine adopts a backward chaining mechanism because it only processes rules that are relevant to the questions and goals. It simply traverses the rule base trying to prove that clauses are true in a systematic manner. The rule is triggered, if all antecedent clauses are set to be true. The clause conditions are derived for each vehicle type.

Knowledge Base

The knowledge bases can be represented by production rules. These rules consist of a condition or premise followed by an action or conclusion (IF Condition .. THEN Action). Most of the rules for weather expert systems are derived from weather contingency rules developed over several years by NASA. Depending upon the type of launch vehicle, rocket propellant and payload, the weather rules change. The knowledge base consists of rules for GO and NO-GO situations. Depending on the prevailing weather conditions the expert system advises the end user. The details of Rawinsonde and other weather parameters form inputs for the toxic gas dispersion model.

Toxic Gas Dispersion Model

The required inputs for the gas dispersion model are vertical profiles of wind direction, wind speed, air temperature, atmospheric pressure and dew point or relative humidity between the earth's surface and 3000 m. This information is obtained during launch support activities from Rawinsonde measurements routinely measured at scheduled times throughout the pre-launch count down and after launch has occurred. The wind system is a series of 30 m towers located throughout Kennedy Space Center and one 152 m meteorological tower instrumented to measure wind direction, wind speed, turbulence and air temperature. Based on the inputs, the toxic gas dispersion model computes the dimensions of the ground cloud as a function of the height, distribution of vehicle exhaust products within

the cloud as a function of height, and position in space of the rising ground cloud as a function of time after launch until the internal cloud temperature equals the ambient air temperature (Boyd 1985; and Beychok 1995). The dosage concentration at an interval of 1 km from downwind of the launch pad is computed. For a normal launch, the assumption is made that all engines and the pad deluge system operate normally. In the case of a launch failure (single engine burn on pad), one solid engine does not ignite and the vehicle remains on the launch pad. In case of failure to lift off, an on pad explosion will cause scattering of solid rocket propellant. The fuel expenditure rates for normal launches are obtained by averaging fuel expenditure rates for the engines over the approximate period from lift off until the vehicle is about 3000 m above the surface. The fuel expenditure rates for the single engine burn are an average for the normal firing period of the engine. The exhaust cloud constituents are HCL, CO_2, and CO. The input to the toxic dispersion model is shown in figure 4.

Figure 4 Inputs for toxic gas dispersion model
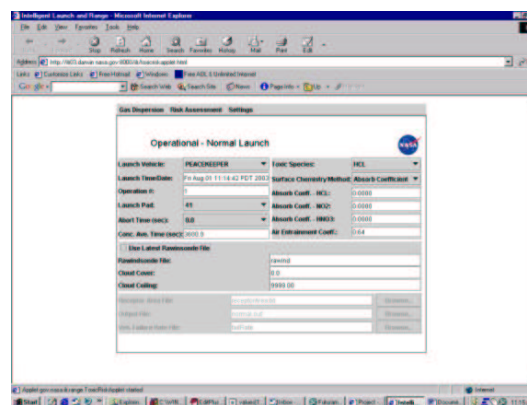
In figure 4, the user can select type of rockets, launch time and date, launch pad (39 A or B), concentration period (ie 1 hour) interval, cloud cover, Rawinsonde data, chemical species (HCL, NO_2, and HNO_3), surface chemistry and necessary coefficients. Once the user has provided all details, the backend of the server using FORTRAN code, computes chemical concentration at the ground level for a particular species. The chemical dosage is converted into contours and it is displayed in figure 5 via *openmap* interface. The concentration is expressed in parts per million (ppm) and five levels of contours are computed from minimum to maximum concentration. The contour simulation is performed by an applet. The

concentration computed at the ground is available for humans to inhale. The flight launch rules have an allowable limit of ground concentration for specific chemicals. If the simulated concentration exceeds the allowable limit, the mission will be kept on hold. The chemical concentration is monitored by real time sampling of ambient air after launch. The real time data and simulated data are compared and act as a surrogate data for other launches.
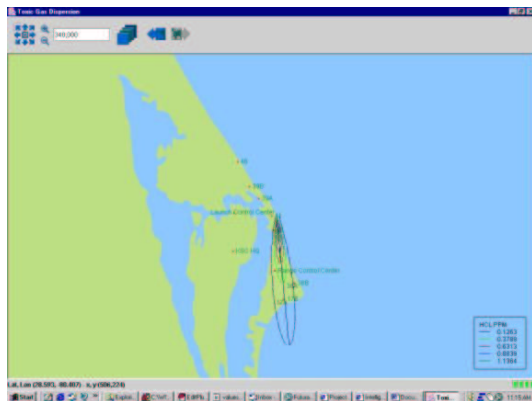

Figure 5 Chemical gas dispersion contour (HCL)

Human Health Risk Assessment Model

A binomial distribution is used to simulate the variance (uncertainty) associated with the predicted number of people affected. The potential for combined effects of exposure to more than one compound is estimated by developing joint probabilities of effect from the individual toxicants probabilities of effect. The LATRA model estimates for HCL, NO_2, and HNO_3 risk assessment. The available toxicological data for humans on the specified rocket emission toxicants are currently limited. The exposure response functions in the LATRA model are currently based on 1 hr time weighted average concentrations and ceiling values. Until more toxicological data is available, the hazard quotient model would be the most appropriate, which is developed by USEPA. The hazard quotient is the ratio of an observed or predicted exposure to an allowable exposure. The allowable exposure limit is set at a lower value by selecting an uncertainty factor that is sufficient to protect sensitive individuals. When the ratio of estimated exposure concentration (EEC) to the reference toxicity vale (RTV) value is less than 1, effects are considered unlikely. When the quotient is greater than 1, some effects might occur in some individuals. As the value of EEC/RTV increases, both the severity and

incidence of effect are likely to increase, but the ratio is not used to predict incidence or severity. An additional advantage of the hazard quotient model is that it allows an estimation of the number of people at risk of additive effects from simultaneous exposure to two or more substances that is not possible in a traditional risk assessment. The risk to the exposed population is calculated by multiplying the individual risk and the number of exposed population (this should take into consideration age, other susceptibility factors, population activities etc.). In our model, the risk value is computed for a given latitude and longitude in a specified region of interest. The risk contour is generated based on the risk values and five levels of contour are plotted. The values are expressed in terms of 1 in million. The risk values are compared against the acceptable risk values and GO and NO-GO status is decided for the launch.
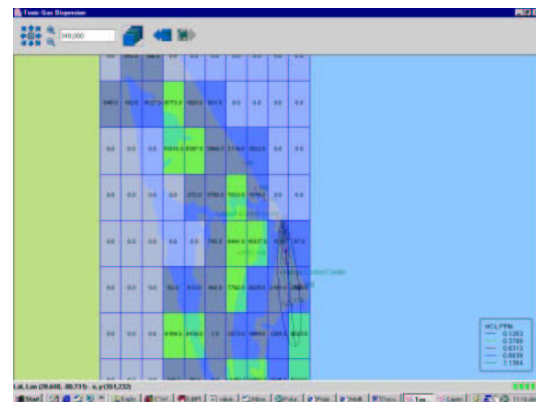

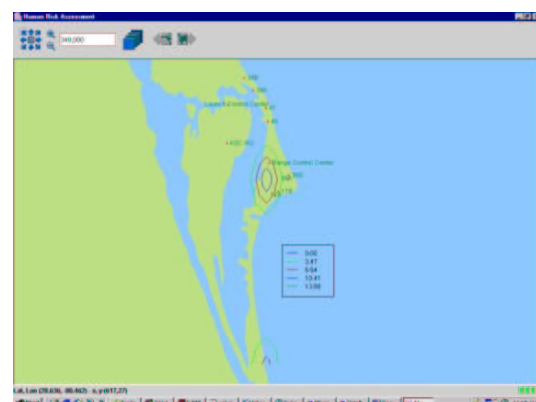Figure 6 Population grid over Cape Canaveral

Figure 7 Human health risk contour

The figure 6 shows a population grid and it is added as a layer in *openmap*. The user can define any number of layers and it can be added dynamically. The population grid displays a selected region of interest and divides into 10 x

10 grids of equal intervals. The centroid of each square is computed by adding all population in the grid. The computed chemical concentration and population is translated into risk values based on the hazard quotient model. The risk contour is shown in figure 7. Presently two dimensional contours are plotted and a zoom feature is added via *openmap* interfaces.

Debris Dispersion Model

Range safety personnel evaluate various scenarios of failure during a launch. If there is a malfunction in separation of rockets, or any failure Range Safety Officers decide to terminate the mission. During termination, flight safety personnel will see that there is a minimum impact of debris scattering near inland. There are various flight rules before destructing the mission. In the present debris dispersion model, gravitational effect is implemented with air resistance. Wind effects are not considered. The debris dispersion model is developed in Java 3D with orbital dynamics. Presently all models interact with four web servers by issuing http requests. Since models are web based, it is easy to access from different corners of the world.

CONCLUSIONS

The complex launch and range safety models are served by four dedicated web servers. Furthermore we are enhancing support for ground operations by adding dedicated web servers. The test bed simulation combines physical model and decision models written in different languages to a unique test bed to visualize complex operations. Further research is planned to develop intelligent agents for each simulation and a decision support system to fully automate space launch initiatives. Since we use Java, it is compatible with any platform and operating system. Each class file in Java can be converted to an applet, Servlet, an application or a library in jar file. The virtual test bed technology enables an entire suite of applications and models for launch and range safety operations.

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AUTHOR BIOGRAPHIES

Jorge Bardina, Ph.D. works at NASA Ames Research Center in the Computational Sciences Division. He is leading the development of the Intelligent Launch & Range Operations, a part of NASA's Intelligent System program in collaboration with Kennedy Space Center. He

also leads the development of Virtual Flight for the design of future space planes with piloted flight simulation. The vision of the RITE Program at Ames Research Center is to merge advanced information technologies to facilitate simulation as an integral part of the design process. His areas of interests are simulation of collaborative team environments involving web-based architectures and engineering technology models.

Rajkumar Thirumalainambi, Ph.D. is a Computer Scientist at Science Application International Corporation (SAIC), working for NASA Ames Research Center, Moffett Field, California, USA. His research interests are neural networks, fuzzy logic, genetic algorithms, computer simulation and modeling. He is involved in building a virtual test bed for real time simulation of space vehicles using artificial intelligence techniques.